Optimization of optical systems for LED spot lights concerning the color uniformity

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ABSTRACT

Spotlighting is one illumination field where the application of light emitting diodes (LED) creates many advantages. Commonly, the system for spot lights consists of a LED light engine and collimating secondary optics. Through angular or spatial separated emitted light from the source and imaging optical elements, a non uniform far field appears with colored rings, dots or patterns. Many feasible combinations result in very different spatial color distributions.
Several combinations of three multi-chip light sources and secondary optical elements like reflectors and TIR lenses with additional facets or scattering elements were analyzed mainly regarding the color uniformity. They are assessed by the merit function U_{sl} which was derived from human factor experiments and describes the color uniformity based on the visual perception of humans. Furthermore, the optical systems are compared concerning efficiency, peak candela and aspect ratio.
Both types of optics differ in the relation between the color uniformity level and other properties. A plain reflector with a slightly color mixing light source performs adequate. The results for the TIR lenses indicate that they need additional elements for good color mixing or blended light source. The most convenient system depends on the requirements of the application.

Keywords: Spot light, color uniformity, non imaging optics, LED illumination, collimation optics

1. INTRODUCTION

Illumination with LED light sources has become very popular due to their advantages in efficiency, life time, system size and design. Spot lights represent an application field which has high requirements. They need to make use of the advantages for high quality lighting. They are mainly used in shop lighting and hospitality to highlight major objects or important areas. Usually, LED spot lights consist of a LED light engine and a collimating optics. A luminance distribution with a defined full width half maximum angle (FWHM) and high peak candela can be reached. Among others, the color uniformity has to be tracked and there may occur inhomogeneities in the far field of the spot because of spatial separated emitted light and optical elements [1]. A uniform spatial color distribution enhances the light impression clearly but the colors and patterns disturb it. A well-fitting combination of light source and collimator is essential for best performance. The color uniformity in the far field is in the focus of the investigation. Three different light sources were combined together with reflectors and total internal reflection (TIR) lenses with additional color mixing elements. The level of color uniformity is evaluated by a merit function U_{sl} which is based on human factor studies and contains the implementation of the visual color perception. It enables the objective analysis of different far fields of spot lights.

2. COLOR UNIFORMITY

The merit function U_{sl} provides a possibility to evaluate measurements and optical simulations regarding their color uniformity level. The formula avoids subjective evaluations by single persons. It realizes a standardized analysis of the far field of spot lights by the implementation of many visual influence factors. Hence, is enables forecasts about the color uniformity level in spot lights.

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2.1 Definition of the merit function for color uniformity

Till now, it has been difficult to make an objective evaluation of color uniformity [2]. For this purpose, the merit function U_{sl} which is explained in detail in [3], was previously derived from human factor experiments. A linear regression of previously defined single functions resulted in U_{sl}. The single functions are related to several visual aspects like contrast sensitivity, symmetry detection and color perception.

$$U_{sl} = a_1 Grad + a_2 \Delta ab + a_3 S_{rad} + a_4 S_{lin} \tag{1}$$

The function *Grad* expresses the gradient and calculates the difference in color between surrounding pixels. The function Δab describes the mean of the color difference between each pixel and the reference color. S_{rad} and S_{lin} refer to the smoothness of the radial and linear color gradient. They were implemented to detect strong aberrations either on several radii or angular axes. The coefficients a_1, a_2, a_3 and a_4 are optimized to reach high correlation between U_{sl} and the perceived rank order from the human factor experiment. Additional enhancements were reached through the application of the contrast sensitivity function (CSF) [4] and the equalization of the slope of the single functions.

A second human factor experiment was performed to define color uniformity levels within U_{sl}. The subjects had to assign marks to each spot light. The results of the experiment defined the levels from excellent to insufficient color uniformity (Figure 1.).

Figure 1. Scale of color uniformity levels for U_{sl} values based on visual color perception.

2.2 Validation of color uniformity U_{sl} in measurements and simulations

The color uniformity U_{sl} was derived from a human factor experiment together with measurements of the test spot lights with a luminance meter. Afterwards, the adjustment of spot light data from optical simulations to the function was required. U_{sl} is applicable in simulations as a reliable calibrated number if the results of measurement and simulation of the same system lead to the same values. The measurements and simulations of four optical systems (Figure 2.) were compared with each other. All four optics were available from manufactures (1, 2) or as prototypes (3, 4).

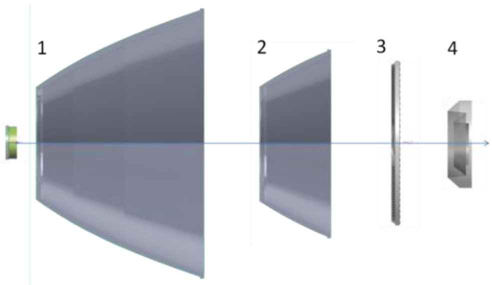

Figure 2. Adjustment of measurements and simulations with multicolored LED light engine (left) and four secondary optics. 1) large reflector with specular reflection, 2) small reflector with Gaussian reflection, 3) Fresnel lens with facets and 4) TIR-Fresnel lens.

In combination with a multicolored LED light source (Figure 4, 1), the far field of each optical system appears different (Figure 3).

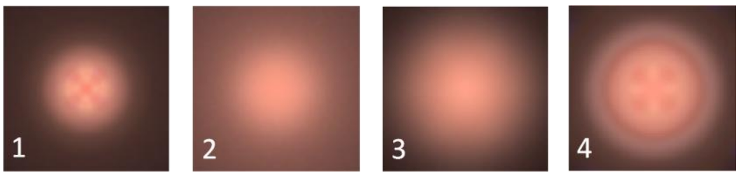

Figure 3. Far fields of the optical elements 1-4 (Figure 2) which were compared in 2 m distance.

The measurements were done with a luminance meter which records the tristimulus values X, Y and Z of the CIE 1931 color space. The light source was about 2 m in front of the projection screen. A realistic model of each system was designed for simulation. The number of rays and the receiver resolution were adjusted to meet the properties of the measurements. The resolution for the 1m² measuring zone was set to 100 x 100.

The four systems have different levels of color uniformity in the far fields. There are two systems (2 and 3) with good color uniformity levels and two systems (1 and 4) with poor color mixing ability.

Table 1. Technical specification of the optical elements (Figure 2) and comparison of U_{sl} for measurements and simulations.

Optical element	Specification (height x length in mm)	FWHM	Measurement U_{sl}	Simulation U_{sl}	Deviation in %
1) Reflector 1	120 x 70	10°	59	61	3 %
2) Reflector 2	80 x 30	15°	28	31	10 %
3) Fresnel lens	60 x 3	17°	32	35	9 %
4) TIR-Fresnel lens	30 x 8	24°	122	115	6 %

Although the optical systems are very different, the deviation between measured and simulated U_{sl} is not larger than 10 %. On the one hand, the differences are based on measurement noise and systematical errors. On the other hand, the models for simulation have limitations. There is a discrepancy between the ideal model and the manufactured prototype, the statistical significance is limited to the number of rays per simulation and per receiver array. The simulation is only a approximation of the prototype. Furthermore, the accuracy of the light source depends on complex physical processes like phosphor conversion and advanced scattering. The calculated difference is within inaccuracies of measurement and simulation itself.

As a result, U_{sl} is reliable in the same way for measurements and simulations. It is applicable as a standardized value for the objective evaluation of the color uniformity in the far field of spot lights and calculates the level in relation to the visual perception.

3. OPTICAL SYSTEM DESIGN

The optical systems consist of the LED light engine and the secondary optics. The optimization was concentrated on the optical elements. Three different multicolored LED light sources (Figure 4.) were used to evaluate the color mixing ability of the systems. Several reflectors, TIR lens and additional mixing elements were used. The different optical systems are compared regarding their color uniformity level and efficiency. There is a variety of color uniformity levels depending on the combination of light source, secondary optics and scattering elements.

3.1 LED light source

The light source is a multicolored LED light engine. It consists of red, blue and phosphor converted white LED chips with a diameter of 9 mm. The three selected light sources differ only in their settings of the scattering layer (Figure 4). The scattering layer is the cast above the LED chip level containing a defined number of Al_2O_3 particles. The spatial separated colors from the LED chips are mixed according to the density of the particles.

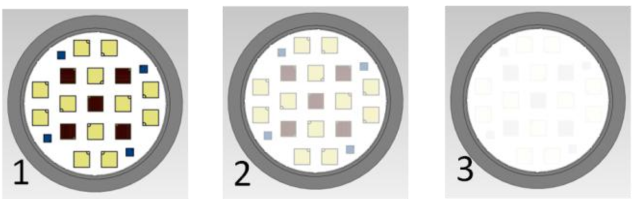

Figure 4. Top view of the three multichip LED light engines with different scattering layers.

Light source 1 has no scattering particle included. The colors of the single LED chips are not mixed inside the light source. The scattering layer of 2 includes few particles and light source 3 contains most particles. Due to the scattering particles, the separated colors were already mixed before the light goes through the secondary optics. A higher number of particles is necessary for better color mixing, but is also decreases the amount of outcoupled light (Table 2.).

Table 2. Optical properties of the three light sources.

Light Source	Description	Relative Efficiency
Light source 1	Clear cast, no scattering layer	100 %
Light source 2	Low Al_2O_3 particle density	99.5 %
Light source 3	High Al_2O_3 particle density	94.9 %

3.2 Secondary optics

There are many different secondary optics which can be applied for beam shaping and color mixing [5]. The LED light engines were combined with different reflectors (Figure 5.) and TIR lenses (Figure 6.). These optical elements are commonly used in spot light designs [6].

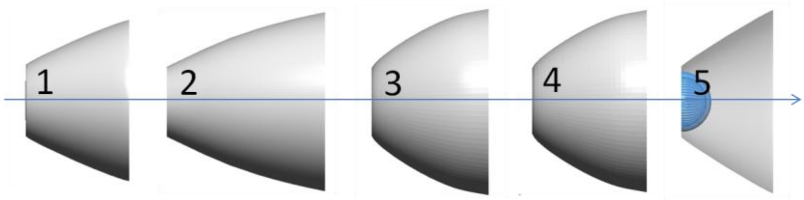

Figure 5. Simulated reflectors, 1) plain reflector, 2) parabolic reflector, 3) reflector with 100 horizontal facets, 4) reflector with 100 horizontal and 50 vertical facets and 5) reflector with Shell mixer.

Facets or scattering areas were added to both types of optics to change the color uniformity level but probably this affects the efficiency. To reflector 5 the Shell mixer[7] was added. It is a shell-shaped element with microlenses to mix the light according to Köhler integration. The diameter of the reflectors is about 45 mm to 50 mm. The TIR lenses have a diameter of 30 mm to 50 mm.

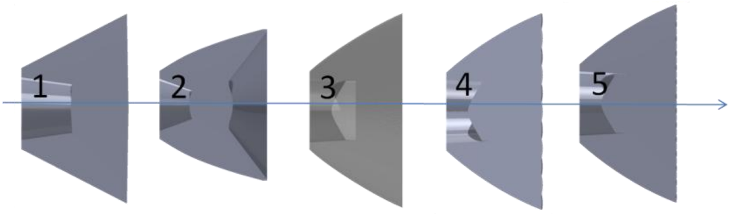

Figure 6. Simulated TIR lenses, 1) and 2) standard TIR lens, 3) with rough outer shell, 4) with large facets (10x10) and 5) with small facets (18x18).

The simulation of the optical system is based on predefined conditions. Each system was analyzed by the same values of efficiency, size and peak candela. For that purpose, each system was optimized to a FWHM angle of 20° ±1, and to high luminance value in the center of the far field. The analysis was carried out after the simulation with 500 million rays. A receiver in a distance of 2 m recorded the analyzed values. The efficiency is specified by the total flux at a receiver shortly after the last surface of the optical system.

4. RESULTS

The requirement for color mixing depends mainly on the application, the ability of mixing in the light source and type of secondary optics. It is necessary to define main aspect for specified applications to be able to select the most suitable combination of LED light engine and optical element because there are differences in the color mixing ability of reflectors and TIR lenses.

4.1 Performance of reflectors

The plain reflectors reach highest efficiencies but the color uniformity level is insufficient in combination with light source 1. The color uniformity level with light source 2 and 3 is similar to other reflectors. Best performance is reached with light source 2 because the color uniformity is improved considerably and the efficiency decreases only a bit. Light source 3 improves the color uniformity sufficiently but the system is less efficient. The three other reflectors with facets and rough outer shell perform similar in efficiency and color uniformity. The color uniformity is improved with light source 2 and best with light source 3. The discrepancy in efficiency is highest between light source 2 and 3. The Shell mixer provides the best color uniformity with all light sources, but it has the lowest efficiency. The efficiency is decreases because of the additional element and its Fresnel losses. Actually, the color uniformity level in combination with light source 1 is better than all other reflectors.

Table 3. Simulation results for U_{sl} and total flux (in lm) for several combinations of light source and reflector

Light source	1) Plain reflector		2) Parabolic reflector		Rough Reflector		3) Faceted Reflector		4) Faceted reflector		5) Shell mixer and reflector	
1	115	1844	145	1857	61	1793	109	1796	87	1770	21	1574
2	53	1838	46	1852	46	1787	57	1790	57	1766	22	1571
3	28	1752	28	1764	28	1709	29	1710	29	1690	13	1428

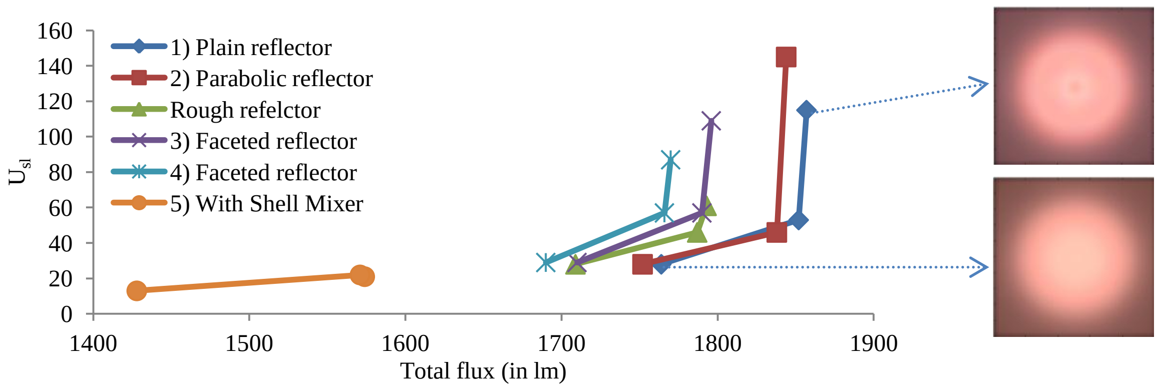

Figure 7. Left: Comparison of the color mixing level and the optical system efficiency for reflectors. Right: Far field of the spot lights of standard reflector 1 with light source 1 (above) and light source 3 (below)

A good color uniformity level can be reached with plain reflectors. No additional mixing elements are needed if the light source provides some color mixing and the efficiency decreases only a bit. For very good color mixing, the Shell mixer could be applied but with noticeable loss of efficiency.

4.2 Performance of TIR lenses

In general, the color uniformity level of the TIR lenses is worse. The two standard TIR lenses perform different. The comparison of lens 1 and 2 shows that lens 2 has a weaker performance because the efficiency is lower and the color uniformity is worse. The color uniformity level does not reach a very good level for both lenses. The insufficient color mixing is based on the imaging properties of the central part of the lens. A rough outer shape has no advantage for color mixing expect decreased efficiency. Facets can improve the color uniformity level. It is important to implement facets with a suitable dimensioning because there is a difference in the color uniformity between the TIR lens with large and small facets. The small facets improve the color mixing clearly and the decrease of efficiency is low.

Table 4. Simulation results for U_{sl} and total flux (in lm) for several combinations of light source and TIR lens

Light source	1) Standard lens		2) Standard lens		3) Lens with rough outer shell		4) Lens with large facets		5) Lens with small facets	
1	118	1822	179	1786	114	1750	77	1760	29	1755
2	76	1818	109	1782	76	1746	52	1754	26	1749
3	36	1733	40	1713	31	1664	25	1670	20	1665

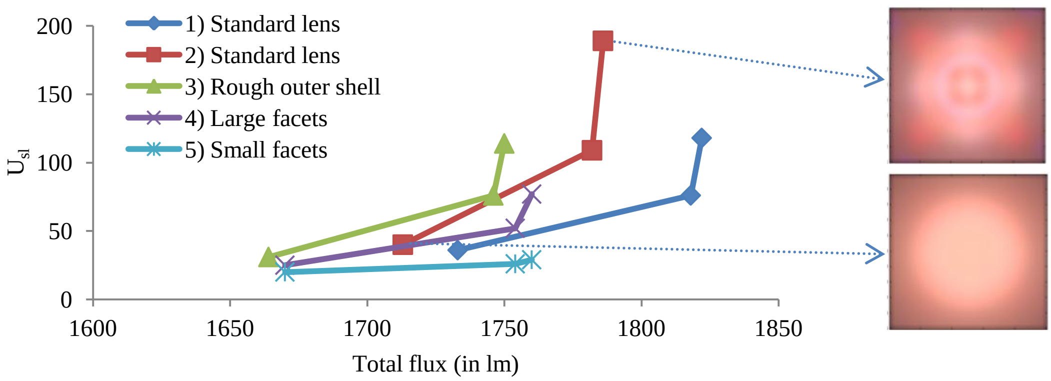

Figure 8. Left: Comparison of the color mixing level and the optical system efficiency for TIR lenses. Right: Far field of the spot lights of standard TIR lens 2 with light source 1 (above) and light source 3 (below)

There is no definitely preferable TIR lens with high efficiency and a good color uniformity level. Either the efficiency is high (standard lens 1) or the color uniformity level is good (lens 5 with small facets).

4.3 Comparison of reflector and TIR lens

There is a difference in the color mixing characteristics. The color mixing can be performed in the light source or in the secondary optics or in both parts. Reflectors need no additional mixing elements if the light source provides some color mixing. Additional elements or good color mixing in the light source is necessary for TIR lenses.

TIR lenses can reach higher center intensities in the spot (Figure 9.) in comparison to reflectors. Additional elements decrease the peak intensity in reflectors as well as in TIR lenses clearly. The additional mixing elements change the intensity distribution. The amount of light outside the FHWM angle is increases because the mixed light is spread for mixing.

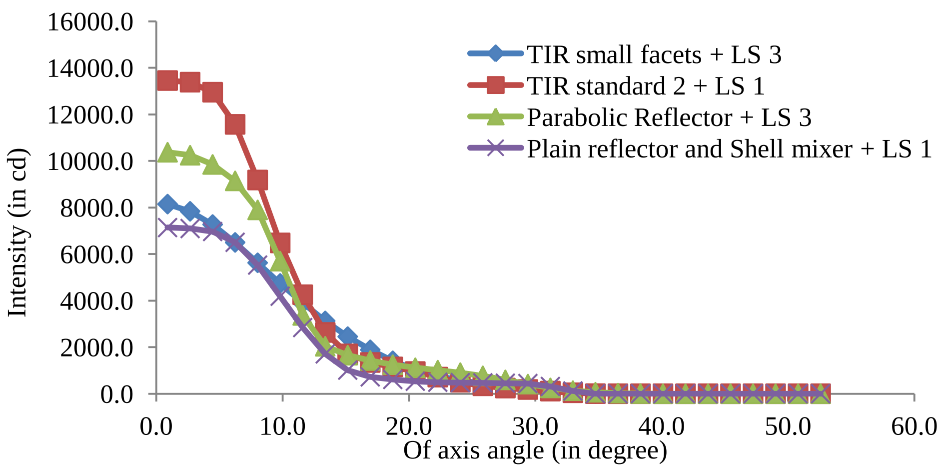

Figure 9. Diagram of intensity over angle for selected systems

None of the groups is definitely superior. Under certain conditions, reflectors show slightly advantages in efficiency at good color uniformity levels. TIR lenses have a higher efficiency at very good color uniformity levels but they need implemented color mixing elements. Each group has its own assets which have to be utilized depending on the application of the spot light.

5. CONCLUSION

The merit function U_{sl} is applicable as a standardized evaluation value for the color uniformity in the far field of spot lights. Several reflectors and TIR lenses were assessed regarding their color uniformity level. There is a wide spectrum of color mixing levels in far field of these optical systems. It is necessary to distinguish between the color mixing in the light source or optical element. For reflectors the color mixing is best in the light source. Here, the decrease of efficiency is low but the contribution to the color uniformity level is high. A light source with some scattering particle and plain reflector receive best relation between efficiency and color uniformity. TIR lenses do not show such an explicit result. For good color mixing level additional elements like facets are needed but they decrease the efficiency. Standard TIR lenses are not adequate for multicolored LED light engines. It is necessary to know the field of application for the spot lights to select the suitable combination of light source and secondary optics.

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